Delayed-Onset Muscle Soreness: Temporal Assessment With Quantitative MRI and Shear-Wave Ultrasound Elastography

OBJECTIVE. The objective of our study was to assess delayed-onset muscle soreness (DOMS) over time using quantitative MRI and shear-wave ultrasound (US) elastography.

SUBJECTS AND METHODS. Five male (mean age ± SD, 39.6 ± 4.6 years) and five female (30.6 ± 13.5 years) volunteers underwent 1.5-T MRI before and after (15 minutes, 1 day, 3 days, 7 days) performing unilateral eccentric resistance exercise of the elbow flexor muscles. The MRI examinations included fluid-sensitive, DWI, and diffusion-tensor imaging sequences of the distal upper arm. Muscle edema, apparent diffusion coefficient (ADC), and fractional anisotropy (FA) were assessed. US of the brachialis muscle was performed before and after (15 minutes, 12 hours, 1 day, 2 days, 3 days, 7 days) exercise to measure mean shear-wave velocity (SWV). Pain and muscle tightness were assessed.

RESULTS. For men, muscle edema was moderate and peaked 3 days after exercise; for women, muscle edema was mild and peaked 1–3 days after exercise. ADC was highest 3 days after exercise in men (mean, 1809.22 × 10–6 mm²/s; before exercise, 1529.88 × 10–6 mm²/s) and women (1741.90 × 10–6 mm²/s; before exercise, 1475.80 × 10–6 mm²/s). FA dropped from 361.00 in men and 389.00 in women before exercise to a minimum of 252.12 and 321.28, respectively, 3 days after exercise. Mean SWV increased after exercise in men (before exercise, 3.00 ± 0.30 m/s; peak [1 day after exercise], 3.23 ± 0.40 m/s) and women (before, 2.82 ± 0.40 m/s; peak [1 day after exercise], 3.23 ± 0.40 m/s) and subsequently returned to normal. In men, the ADC values of the brachialis muscle positively correlated with mean SWV (r = 0.92, p = 0.028). FA negatively correlated with pain in men (r = –0.993, p = 0.001) Muscle edema outlasted clinical symptoms in most volunteers.

CONCLUSION. FA inversely correlates with pain and may be a useful imaging parameter for assessment of DOMS. Shear-wave US elastography shows a temporary increase of muscle stiffness after DOMS-inducing exercise but does not correlate with quantitative MRI parameters or clinical symptoms.

delayed-onset muscle soreness (DOMS) is a familiar experience for athletes and typically presents with muscle tightness, aching pain, or muscular tenderness [1–7]. DOMS typically presents 24 hours after the athlete has completed the exercise, peaks within 24–72 hours after exercise, and slowly resolves after 5–7 days [4, 5]. DOMS is thought to be caused by eccentric forces (i.e., muscle-lengthening forces) that are unaccustomed to or are too strenuous for the corresponding muscle belly, inducing injury to muscle fibers [2, 7].

The molecular and cellular mechanisms of DOMS are not yet completely understood. Several theories include inflammation, muscle spasm, microtrauma, connective tissue damage, shift of electrolytes, enzyme efflux, lactic acid accumulation, or a variable combination of these factors [4, 7–9]. Some studies have already confirmed that MRI [10–16] and ultrasound (US) elastography [17–21] can depict changes in muscle tissue after exercise. However, the temporal evolution of DOMS-related muscle changes detected on MRI and their correlation with US elastography are unknown. Therefore, the purpose of our study was to evaluate the appearance of DOMS over time using MRI (i.e., fluid-sensitive, DWI, and diffusion-tensor imaging [DTI] sequences) and shear-wave US elastography.

Subjects and Methods

This study was approved by the local ethics committee. Informed consent was obtained from
all participants. The study setup consisted of an eccentric resistance exercise of the elbow flexor muscles of the nondominant arm to induce DOMS. All volunteers were prospectively included in the study. The inclusion criteria were age of more than 18 years, no experience or little experience with weight-lifting exercises, and no history of DOMS or other clinical symptoms in the tested arm during the 14-day period before study participation.

**Pilot Trial**

We performed a pilot run at the beginning of this study to choose target muscles for the US examination and to prove the feasibility of the study setup. Two asymptomatic volunteers underwent eccentric exercise of their nondominant arm with individually chosen weights, as described later in detail. Muscle edema was found only in the brachialis muscle on MR images in these two volunteers after successful induction of DOMS.

The study schedule, as shown in the flowchart in Figure 1, was as follows: Shear-wave US elastography was performed before the exercise (time 0) and 15 minutes, 12 hours, 1 day, 2 days, 3 days, and 7 days after eccentric resistance exercise. MRI of each volunteer was performed before the exercise (time 0) and 15 minutes, 1 day, 3 days, and 7 days after eccentric resistance exercise. Clinical parameters (i.e., pain and muscle tightness) were assessed before the exercise (time 0) and 15 minutes, 12 hours, 1 day, 2 days, 3 days, and 7 days after eccentric resistance exercise. Note that the US examination was performed 10–15 minutes before the MRI examination, and the clinical parameter assessment took place just after the US examination and before MRI. For simplification, the same time points for US examination, clinical assessment, and MRI examination are stated in this article.

**Delayed-Onset Muscle Soreness Induction**

Under the supervision of a physiotherapist (15 years of experience), all volunteers performed the same concentric exercise to determine the individual weight for the eccentric exercise. After completing a short warm-up, the volunteer sat with the elbow of the nondominant arm placed on the knee. The starting weight was then either increased or decreased (range, 5–20 kg; intervals of 0.25 kg) to find the exact weight with which the volunteer was able to perform no more than one set of 10 repetitions of concentric elbow flexion. The volunteer only actively pulled the weight up (concentric muscle contraction). The weight was taken down by a person assisting the volunteer. This concentric assessed weight was then used to calculate the individual weight for the eccentric exercise in each volunteer. We used the following procedure, which was adapted from [22]: The weight that allowed a maximum of 10 repetitions of concentric elbow flexion was assumed to reflect 75% of the so-called “one-repetition maximum” (IRM). The latter would allow only one concentric elbow flexion. Then, 90% of this individually calculated IRM weight was used for each volunteer in the eccentric DOMS-induction session. The mean weights for DOMS induction were 13.5 ± 3.1 kg for men and 8.2 ± 1.6 kg for women.

The exercise session for induction of DOMS was performed at least 1 week after determination of the exercise weight using the same arm. The exercise is described in detail in Figure 2. The elbow of the nondominant arm was placed on the volunteer’s ipsilateral knee in a sitting position. The weight was then brought down slowly by the volunteer in about 3–5 seconds until full elbow extension was reached. The assisting person put the weight up again while the participant put the arm back in the starting position with a flexed elbow without weight. Overall, the exercise consisted of three sets with 12 repetitions each. The break between each set was 60 seconds.

**Clinical Parameters**

Clinical parameters were assessed immediately after the US examination. Pain was assessed on a numeric ranking scale ranging from 0 (no pain) to 10 (maximal pain imaginable) points. Muscle tightness in the elbow flexor muscles was assessed as either present or absent.

**Shear-Wave Ultrasound Elastography**

Shear-wave US elastography was performed by one of two examiners (both fellowship-trained in musculoskeletal radiology with 8 and 5 years of experience in radiology, respectively). All volunteers were scanned while in a sitting position with the nondominant arm relaxed (Fig. 3). For the US examinations, a US system (Acuson S3000, Siemens Healthcare) with a linear-array transducer with a bandwidth of 4–9 MHz was used. This position was chosen to prevent tension on the brachialis muscle to avoid false velocity measurements because muscle tension can significantly change shear-wave velocity (SWV) measurements [23, 24].

In a pilot trial with two volunteers, as mentioned earlier, we found muscle edema only in the brachialis muscle and therefore decided to assess SWV in that muscle.

For the US examinations, the transducer was positioned as follows to obtain reproducible measurement results: First, the broadest extension of the brachialis muscle was determined in an axial image plane (i.e., perpendicular to the long axis of the muscle belly). Second, the transducer was switched 90° to get a sagittal image plane (parallel to the muscle fibers) (Fig. 4A). A sagittal examination plane was chosen because shear waves propagate better along muscle fibers rather than across them [25]. The SWV (in meters per second) was assessed in the brachialis muscle using dedicated software: Virtual Touch Tissue Imaging Quantification (VTIQ, Siemens Healthcare). In total, 16 measurements were obtained per muscle by acquiring two different velocity images (6.5 and 8.0 m/s) and by manually placing four ROIs randomly in the superficial part and four ROIs randomly in the deep part of the muscle belly on each of the velocity images according to a predefined scheme (Fig. 4A).

With the VTIQ software, SWV can be assessed from 0 to 10 m/s as shown on a color-coded velocity image (Fig. 4A). The software includes a quality map indicating the quality and reliability of the SWV measurements in a color-coded display that uses a “traffic light” scheme (good = green, marginal = yellow, poor = red). Measurements were repeated until an optimal (green) quality map was shown (Fig. 4B). Mean SWV was calculated using all 16 measurements per examination.

**MRI**

All MRI examinations were performed on a clinical 1.5-T MRI scanner (Avanto-Fit, Siemens Healthcare). The volunteers were in the prone position with the elbow and upper arm centered in a 15-channel high-resolution send-receive knee coil (TrxR Knee 15 Coil 1.5 Tesla, Quality Electrodynamics, Siemens Healthcare).

The MRI protocol included a sagittal volumetric interpolated breath-hold examination (VIBE) 3D gradient-echo T1-weighted sequence. The VIBE sequence was performed using the following parameters: voxel size, 0.9 × 0.9 × 0.9 mm; TR/TE, 14.90/6.84; number of signals acquired, 1; matrix, 256 × 256; and FOV, 220 mm. A DWI sequence was performed using the following parameters: voxel size, 1.8 × 1.8 × 1.8 mm; TR/TE, 5200/53; matrix, 122 × 122; and FOV, 220 mm. A sagittal STIR sequence was performed using the following parameters: voxel size, 0.6 × 0.6 × 0.3 mm; slice thickness, 3 mm; TR/TE, 4000/456; number of signals acquired, 2; matrix, 384 × 307; and FOV, 220 mm. A transverse intermediate-weighted fat-saturated turbo spin-echo sequence was performed using the following parameters: voxel size, 0.3 × 0.3 × 0.5 mm; slice thickness, 5 mm; TR/TE, 3000/37; number of signals acquired, 1; matrix, 384 × 268; and FOV, 120 mm.

The sequences were acquired covering the elbow joint and the lower part of the upper arm. Fractional anisotropy (FA) maps were reconstructed from the nondistorted diffusion images using software (SyngoMMWP, version VE36A,
TABLE 1: Shear-Wave Velocity (SWV) and Muscle Tightness in 10 Volunteers

<table>
<thead>
<tr>
<th>Volunteer (Exercise Weight)</th>
<th>Mean SWV (m/s)</th>
<th>Before Exercise (Time 0)</th>
<th>After Exercise</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male 1 (11.0 kg)</td>
<td>3.36</td>
<td>3.59</td>
<td>3.98</td>
<td>3.12</td>
</tr>
<tr>
<td>Male 2 (13.0 kg)</td>
<td>2.45</td>
<td>2.89</td>
<td>3.22</td>
<td>3.12</td>
</tr>
<tr>
<td>Male 3 (16.5 kg)</td>
<td>3.08</td>
<td>3.18</td>
<td>3.18</td>
<td>3.35</td>
</tr>
<tr>
<td>Male 4 (14.0 kg)</td>
<td>3.09</td>
<td>3.17</td>
<td>3.17</td>
<td>3.35</td>
</tr>
<tr>
<td>Male 5 (11.0 kg)</td>
<td>3.01</td>
<td>3.04</td>
<td>3.04</td>
<td>3.16</td>
</tr>
<tr>
<td>Mean SWV for men</td>
<td>3.00</td>
<td>3.04</td>
<td>3.04</td>
<td>3.16</td>
</tr>
<tr>
<td>Female volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female 1 (6.0 kg)</td>
<td>2.49</td>
<td>2.53</td>
<td>2.38</td>
<td>3.14</td>
</tr>
<tr>
<td>Female 2 (8.0 kg)</td>
<td>3.52</td>
<td>3.10</td>
<td>3.17</td>
<td>3.29</td>
</tr>
<tr>
<td>Female 3 (8.0 kg)</td>
<td>2.41</td>
<td>3.35</td>
<td>3.52</td>
<td>3.43</td>
</tr>
<tr>
<td>Female 4 (10.5 kg)</td>
<td>2.90</td>
<td>2.85</td>
<td>2.98</td>
<td>3.51</td>
</tr>
<tr>
<td>Female 5 (8.5 kg)</td>
<td>2.79</td>
<td>2.65</td>
<td>2.85</td>
<td>3.29</td>
</tr>
<tr>
<td>Mean SWV for women</td>
<td>2.82</td>
<td>3.06</td>
<td>3.05</td>
<td>3.14</td>
</tr>
</tbody>
</table>

Note—Boldface indicates presence of muscle tightness.

TABLE 2: Temporal Evolution of Muscle Edema in the Elbow Flexor Muscles of Each Volunteer

<table>
<thead>
<tr>
<th>Muscle and Volunteer (Exercise Weight)</th>
<th>After Exercise</th>
<th>Before Exercise (Time 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Days</td>
<td>15 Minutes</td>
</tr>
<tr>
<td>Brachialis muscle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male volunteers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male 1 (11.0 kg)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 2 (13.0 kg)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 3 (16.5 kg)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 4 (14.0 kg)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 5 (11.0 kg)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Female volunteers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female 1 (6.0 kg)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 2 (8.0 kg)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 3 (8.0 kg)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 4 (10.5 kg)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 5 (8.5 kg)</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

(The Table 2 continues on next page)
MRI and US Elastography of DOMS Over Time

Shear-Wave Ultrasound Elastography

The mean SWV before exercise was 3.00 ± 0.30 m/s in men and 2.82 ± 0.40 m/s in women. In men, there was an increase of mean SWV after exercise that peaked 15 minutes after exercise (4.04 ± 0.90 m/s). Women also showed an increase of mean SWV, but the peak appeared 1 day after exercise (3.23 ± 0.40 m/s). The SWV increase compared with the baseline examination before exercise was less pronounced in women (14.3%) than in men (33.3%). For detailed temporal changes in the mean SWV values, see Table 1.

MRI

Muscle edema—The temporal evolution and location of edema in the elbow flexor muscles for all volunteers are shown in Table 2. Areas with muscle edema in the brachialis muscle were more severe in men than women except in one female volunteer. In the latter female volunteer, severe edema was seen in the brachialis muscle 3 days after exercise (Table 2). A little edema was seen in the biceps brachii on the STIR images of only two volunteers on day 3 and 7, respectively. No edema was seen in the biceps brachii muscle on MRI of all other volunteers.

Maximal muscle edema in men was located in the brachialis muscle in four volunteers. In one male volunteer, maximal muscle edema was located in the pronator teres muscle. In women, maximal muscle edema was located in the brachialis muscle in four volunteers and in the brachioradialis muscle in the remaining volunteer.

Cross-sectional area—The mean CSA of the elbow flexor muscles in men before exercise was 2045.60 mm². In relation to the baseline examination, CSA increased 2.58% 15 minutes after exercise, 6.28% after 1 day, 8.90% after 3 days, and 1.22% after 7 days (Fig. 8). Before exercise, the mean CSA in women was 1175.20 mm²; in relation to baseline CSA, CSA increased 2.86% 15 minutes after exercise, 4.82% after 1 day, 11.49% after 3 days, and 4.00% after 7 days. In men, CSA inversely correlated with FA at the location of the maximal edema ($r = -0.981, p = 0.003$). The correlation between CSA and ADC in men did not reach statistical significance ($r = 0.853, p = 0.066$). In women, CSA inversely correlated with FA ($r = -0.964, p = 0.008$) and positively correlated with ADC ($r = 0.990, p = 0.001$).

Correlation of apparent diffusion coefficient with fractional anisotropy—Temporal changes in ADC and FA values in men and women for the three measured loca-

**TABLE 2: Temporal Evolution of Muscle Edema in the Elbow Flexor Muscles of Each Volunteer (continued)**

<table>
<thead>
<tr>
<th>Muscle and Volunteer (Exercise Weight)</th>
<th>Edema Scorea</th>
<th>Before Exercise (Time 0)</th>
<th>After Exercise</th>
<th>15 Minutes</th>
<th>1 Day</th>
<th>3 Days</th>
<th>7 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biceps brachii muscle Male volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Male 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Female 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Brachioradialis muscle Male volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Male 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Female 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pronator teres muscle Male volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Male 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Female 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Female 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Note—**Boldface** shows muscle with most edema in each volunteer.

a0 = no edema; 1 = little edema (slightly more hyperintense than surrounding muscle); 2 = moderate edema (not little and not severe); and 3 = severe edema (very hyperintense signal intensity, close to vessels).
TABLE 3: Correlation Between Apparent Diffusion Coefficient (ADC) and Fractional Anisotropy (FA)

<table>
<thead>
<tr>
<th>Muscle and Volunteers</th>
<th>Before Exercise (Time 0)</th>
<th>After Exercise</th>
<th>r²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 Minutes</td>
<td>1 Day</td>
<td>3 Days</td>
<td>7 Days</td>
</tr>
<tr>
<td>Brachialis muscle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADC (× 10⁻⁶ mm²/s)</td>
<td>1550.40</td>
<td>1693.60</td>
<td>1680.80</td>
<td>1632.00</td>
</tr>
<tr>
<td>FA</td>
<td>405.50</td>
<td>369.98</td>
<td>342.38</td>
<td>376.66</td>
</tr>
<tr>
<td>Female volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADC (× 10⁻⁶ mm²/s)</td>
<td>1486.40</td>
<td>1575.00</td>
<td>1584.20</td>
<td>1660.60</td>
</tr>
<tr>
<td>FA</td>
<td>426.15</td>
<td>411.42</td>
<td>401.78</td>
<td>414.08</td>
</tr>
<tr>
<td>Biceps brachii muscle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADC (× 10⁻⁶ mm²/s)</td>
<td>1495.20</td>
<td>1742.00</td>
<td>1561.20</td>
<td>1626.40</td>
</tr>
<tr>
<td>FA</td>
<td>337.55</td>
<td>337.58</td>
<td>349.92</td>
<td>342.06</td>
</tr>
<tr>
<td>Female volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADC (× 10⁻⁶ mm²/s)</td>
<td>1511.60</td>
<td>1602.80</td>
<td>1637.80</td>
<td>1590.80</td>
</tr>
<tr>
<td>FA</td>
<td>386.90</td>
<td>395.72</td>
<td>404.48</td>
<td>373.28</td>
</tr>
<tr>
<td>Maximum edema</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADC (× 10⁻⁶ mm²/s)</td>
<td>1529.88</td>
<td>1716.40</td>
<td>1794.38</td>
<td>1809.22</td>
</tr>
<tr>
<td>FA</td>
<td>361.00</td>
<td>351.88</td>
<td>289.42</td>
<td>252.12</td>
</tr>
<tr>
<td>Female volunteers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADC (× 10⁻⁶ mm²/s)</td>
<td>1475.80</td>
<td>1569.30</td>
<td>1591.58</td>
<td>1741.90</td>
</tr>
<tr>
<td>FA</td>
<td>389.00</td>
<td>387.75</td>
<td>362.85</td>
<td>321.28</td>
</tr>
</tbody>
</table>

Note—There was a trend for an inverse correlation between ADC and FA in the damaged brachialis muscle but not in the less loaded biceps brachii muscle.

*Pearson correlation coefficient.

TABLE 4: Correlation Coefficients Between MRI Parameters and Pain

<table>
<thead>
<tr>
<th>Volunteers</th>
<th>Brachialis Muscle</th>
<th>Biceps Brachii Muscle</th>
<th>Muscle With Maximum Edema</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ADC (× 10⁻⁶ mm²/s)</td>
<td>FA</td>
<td>ADC (× 10⁻⁶ mm²/s)</td>
</tr>
<tr>
<td>Male volunteers</td>
<td>0.488 (0.404)</td>
<td>-0.632 (0.253)</td>
<td>-0.076 (0.903)</td>
</tr>
<tr>
<td>Female volunteers</td>
<td>0.763 (0.133)</td>
<td>-0.701 (0.187)</td>
<td>0.695 (0.192)</td>
</tr>
</tbody>
</table>

Note—Boldface indicates statistically significant values. ADC = apparent diffusion coefficient, FA = fractional anisotropy.

Discussion

Our results show the temporal evolution of muscle changes after DOMS-inducing exercise visualized with shear-wave US elastography and quantitative MRI parameters. Our findings show a temporary increase in stiffness (i.e., SWV) of the brachialis muscle after eccentric exercise. Although the peak SWV is shortly after exercise, the maximum FA drop presents 3 days after exercise. FA inversely correlates with pain and may reflect the underlying damage to the muscle ultrastructure better than muscle edema on fluid-sensitive MRI sequences because muscle edema exceeds the clinical symptoms in patients with DOMS.

The increase in SWV is proportional to an increase in tissue stiffness according to the so-called “elastic modulus” (E in kilopascals [26]). More than 30 years ago, Newham et al. [27] reported that eccentric exercise can lead to immediate focal ultrastructural damage of the sarcomeres in the muscle fibers that results in disturbances of myofilibrillar organization that exacerbate during the first 3 days after exercise. On the molecular level, an acute loss of cell membrane–stabilizing proteins (e.g., desmin, dystrophin, and others) within hours after eccentric exercise leads to disorganization of myofilibrils [28–31]. Eccentric exercise leads to rupture of the sarcolemma and opening of mechanosensitive stretch channels in the cell membrane, which results in an accumulation of intracellular Ca²⁺ and Na⁺ ions. These ion influxes not only increase cellular damages and result (via several pathways) in edema, inflammation, and a transient decrease of force production but also act as a stimulus for muscle...
MRI and US Elastography of DOMS Over Time

hypertrophy [32]. Several studies have shown rapid infiltration of inflammatory cells (predominantly neutrophils) into skeletal muscle 45 minutes–2 hours after eccentric exercise to eliminate necrotic cells [33, 34]. Therefore, the observed immediate increase in muscle stiffness after exercise in our volunteers could be explained by the extracellular muscle edema and increased blood flow due to the exercise itself rather than to DOMS.

The peaks in SWVs in our study population (15 minutes after exercise in men and 1 day in women) are slightly different than the results reported by Niitsu et al. [35]. They studied muscle stiffness measured on US elastography and a durometer after eccentric exercise of the nondominant elbow flexors in six male volunteers. The peak stiffness was seen 1–2 days after exercise [35]. However, they used a different kind of US elastography technique (i.e., tissue strain induced by compression).

Yanagisawa et al. [18] confirmed an increase in muscle hardness of the biceps muscle on real-time US elastography performed immediately after eccentric exercise in nine male volunteers. Increased perfusion with exercise produces a pseudohypertrophy of the muscle, and metabolic factors (fatigue) may contribute to the phenomenon, because adenosine triphosphate (ATP) is required to detach myosin from actin during cycles of muscle contraction (swinging cross-bridge model [36]). With ATP loss during exercise, this detachment capacity decreases and the two proteins remain connected. Therefore, ATP loss could be another reason for the increased stiffness observed on shear-wave US elastography.

When looking at the distribution of the maximum edema on STIR imaging, we found that the SWV measurements in the brachialis muscle were often not at the same location as the edema. Water diffusion is dependent on the presence and orientation of physical barriers. Myocyte damage leads to disorganization and a decrease of physical diffusion barriers and, therefore, to an increase of the rate of water diffusion and a decrease in anisotropy. These molecular processes seem to be best reflected by the ADC and FA changes at the location of maximal edema. Several studies have found that injured muscles show increased ADC and decreased FA values in the area of the injury [12, 37]. A similar temporal evolution of FA—that is, the maximum drop 3 days after exercise—was observed in the study by Yanagisawa et al. [37] in the calf muscles.

Another interesting finding was the very strong inverse correlation between pain and FA at the location of the maximal muscle edema. This correlation may reflect the damage to the muscle ultrastructure and the corresponding inflammatory reaction causing pain. Although maximum pain was observed 2 days after exercise, FA was lowest 3 days after exercise. We explain this discrepancy by the fact that we did not perform MRI 2 days after exercise and we assume that FA 2 days after exercise could be even lower. Interestingly, 7 days after the initial exercise, all men showed still muscle edema on STIR images but felt no pain. The muscle edema of DOMS may still be present after symptoms have resolved. However, FA values 7 days after exercise were more or less back to the preexercise levels, reflecting the very strong inverse correlation between FA and pain.

Cleak and Eston [38] assessed several clinical parameters in 26 young women after eccentric exercise of the elbow flexors. They found that upper arm circumference was highest 4 days after exercise. They found a decrease in swelling and almost normalized upper arm circumference 7 days after exercise. Similarly, we found the highest CSA on MR images 3 days after exercise with a steady decrease thereafter. We did not measure on day 4.

We found some differences in the temporal evolution of DOMS between men and women in this study. In women, the presence and severity of muscle edema were less visible on MR images, although the women reported pain levels similar to or even higher than those reported by men. Changes in ADC, FA, and SWV were less pronounced in women than in men. Therefore, imaging may not allow detecting all muscle changes related to pain sensation. Sex differences in muscle response to eccentric exercise could be an explanation for this finding: Sex-specific factors may involve differences in muscle composition, which affects muscle stiffness and inflammation. These sex-specific factors may comprise differences in connective tissue content [39] and muscle fiber–type distribution [40] because these factors affect the capacity for water homeostasis [41]. Also, differences exist in vulnerability between muscle fiber types [42], which likely affects inflammation and water-based muscle tension.

This study has several limitations: The sample size is very small. No correlation of our findings with corresponding changes in plasma protein levels (e.g., creatine kinase or α-actin) or in cellular or histopathologic characteristics could be performed. We did not perform an intra-individual correlation (i.e., with the contralateral non-exercised arm), and US elastography was performed in the brachialis muscle only. Furthermore, the MRI readout was not blinded to time points, and a sampling error could be present when obtaining US and MRI measurements. Some of the volunteers showed muscle edema in muscles other than the brachialis muscle. We attribute this finding to the coordinative challenge of elbow flexion [43], which results in damage of different muscles. Muscle coordination is also dependent on the routine in doing the same motion pattern (i.e., elbow flexion in our study).

In summary, shear-wave US elastography shows a temporary increase in muscle stiffness after eccentric DOMS-inducing muscle exercise but does not correlate with quantitative MRI parameters or clinical symptoms. Muscle edema in patients with DOMS may persist longer (> 7 days after exercise) than clinical symptoms, whereas mean SWV, ADC, and FA values return to approximate preexercise levels 7 days after exercise. FA inversely correlates with pain and may be a good imaging parameter to use to assess DOMS.

References


AJR:208, February 2017 407
19. Koo TK, Guo JY, Cohen JH, Parker KJ. Quantify
20. Chino K, Akagi R, Dohi M, Fukashiro S,
15. Nosaka K, Clarkson PM. Changes in indicators of
10. Baczkowski K, Marks P, Silberstein M,
8. Yoshitake Y, Takai Y, Kaeheisa H, Shinohara M.
5. Elegbe EC, McAleavey SA. Single tracking location
3. Lovering RM, De Deyne PG. Contractile func
2. Chino K, Akagi R, Dohi M, Fukashiro S,

Agten et al.

11. Oudeman J, Nederveen AJ, Strijkers GJ, Maas M,
10. Oudeman J, Nederveen AJ, Strijkers GJ, Maas M,
7. Carpenter EL, Lau HA, Kolodny EH, Adler RS.
calf muscle contraction by diffusion tensor imaging.
5. Nosaka K, Clarkson PM. Changes in indicators of
3. Lovering RM, De Deyne PG. Contractile func
2. Chino K, Akagi R, Dohi M, Fukashiro S,

\[ \text{(*)} \]

\[ \text{(**)} \]

\[ \text{(***)} \]

\[ \text{****} \]

\[ \text{*****} \]

\[ \text{******} \]

\[ \text{*******} \]

\[ \text{********} \]

\[ \text{*********} \]

\[ \text{**********} \]

\[ \text{***********} \]

\[ \text{************} \]

\[ \text{*************} \]

\[ \text{**************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]

\[ \text{***************} \]

\[ \text{****************} \]
Fig. 1—Flowchart shows study protocol. US = ultrasound.

Fig. 2—Photograph shows eccentric resistance exercise performed by volunteers. In sitting position, volunteer (V) placed elbow of nondominant arm on ipsilateral knee and brought weight down (arrow) slowly in approximately 3–5 seconds until elbow was fully extended (eccentric resistance exercise). Assisting person (A) took weight from volunteer while volunteer brought his or her arm back to starting position with flexed elbow without weight.

Fig. 3—Shear-wave ultrasound elastography. Photograph shows position of arm for scanning: Volunteer rests wrist on pillow and relaxes brachialis muscle, and transducer is parallel to long axis of brachialis muscle belly.

Fig. 4—Color-coded shear-wave ultrasound elastography maps of 40-year-old male volunteer (male volunteer 5 in Tables 1 and 2). Maps were obtained using Virtual Touch Tissue Imaging Quantification (VTIQ, Siemens Healthcare) software. A, Color-coded map obtained before exercise shows shear-wave velocities (SWVs) and positioning of ROIs in superficial and deep portions of brachialis muscle belly. B, Quality map for A. Quality maps are provided by software to indicate quality and reliability of SWV measurements (HI = high quality [green], LO = low quality [red]). Measurements were repeated until map showing optimal quality, like map shown here, was obtained.

(Fig. 4 continues on next page)
Agten et al.

Fig. 4 (continued)—Color-coded shear-wave ultrasound elastography maps of 40-year-old male volunteer (male volunteer 5 in Tables 1 and 2). Maps were obtained using Virtual Touch Tissue Imaging Quantification (VTIQ, Siemens Healthcare) software. 

C, Color-coded map obtained 15 minutes after exercise shows shear-wave velocities (SWVs) and positioning of ROIs in superficial and in deep portion of brachialis muscle belly.

D, Quality map (HI = high quality [green], LO = low quality [red]) for C shows SWV measurements are optimal quality and reliability.

Fig. 5—Images of 40-year-old male volunteer (male volunteer 5 in Tables 1 and 2 [also shown in Fig. 4]) obtained 3 days after eccentric resistance exercise of elbow flexor muscles on right side.

A, Sagittal STIR MR image (TR/TE, 4000/456) shows severe edema in brachialis muscle.

B, Fractional anisotropy map shows ROI in brachialis muscle (red circle) and biceps brachii muscle (green circle).

Fig. 6—39-year-old male volunteer (male volunteer 1 in Tables 1 and 2) obtained 3 days after extrinsic resistance exercise of elbow flexors muscles on right side. Transverse intermediate-weighted fatsaturated turbo spin-echo image (TR/TE, 3000/37) shows marked muscle edema related to delayed-onset muscle soreness (DOMS) in brachialis muscle (1), no edema in biceps brachii muscle (2), marked muscle edema related to DOMS in brachioradialis muscle (3), and no edema in extensor carpi radialis longus muscle (4). Cross-sectional area (dotted line) of flexor compartment was measured just proximal to level of pronator teres muscle to include all mentioned muscles because separation of muscles was often not possible. Arrow shows adjacent soft-tissue edema in subcutaneous fat.
MRI and US Elastography of DOMS Over Time

Fig. 7—Temporal changes in mean pain levels (according to numeric ranking scale from 0 [no pain] to 10 [maximal pain imaginable]) from delayed onset of muscle soreness for men and women were similar. Maximum pain was reported 2 days after eccentric resistance exercise. Seven days after exercise, all participants were pain-free.

Fig. 8—Cross-sectional area (CSA) of elbow flexor muscles of upper arm was measured manually proximal to origin of pronator teres muscle on transverse intermediate-weighted fat-saturated MRI sequence. CSA peaked 3 days after exercise in both men and women. In men, CSA on day 3 had increased 8.9% compared with CSA before exercise; in women, CSA on day 3 had increased 11.5% compared with CSA before exercise.

Fig. 9—Graphs show fractional anisotropy (FA) and apparent diffusion coefficient (ADC) values of brachialis muscle, biceps brachii muscle, and location with maximal muscle edema in male and female volunteers before and after exercise. A and B, FA (A) and ADC (B) values for brachialis muscle. FA values decreased little in brachialis muscle 1 day after eccentric resistance exercise and returned to normal 7 days after exercise. ADC values showed small increase.

(Fig. 9 continues on next page)
Fig. 9 (continued)—Graphs show fractional anisotropy (FA) and apparent diffusion coefficient (ADC) values of brachialis muscle, biceps brachii muscle, and location with maximal muscle edema in male and female volunteers before and after exercise. No relevant changes in FA were found in biceps brachii muscle, and ADC values showed small increase. Decrease in FA values was more pronounced and peaked 3 days after exercise. ADC values showed small increase.
This article has been cited by:


4. Hsin-Fu Lin, Yi-Hung Liao, Pai-Chi Li. 2021. Ultrafast Ultrasound-Derived Muscle Strain Measure Correlates with Carotid Local Pulse Wave Velocity in Habitual Resistance-Trained Individuals. Applied Sciences 11:18, 8783. [Crossref]


9. Iris Kilsdonk, Danoo Dalili, Anne D. van der Made, Mario Maas. Monitoring of Muscle and Tendon Repair 783-793. [Crossref]

10. Mahdi Al-Qahtani, Omar Altuwaijri, Meteb Altaf, Majed Al-Enezi, Mahmoud Abulmeaty, Ravish Javed. 2020. Influence of body mass index and weight lifting on bicep brachii muscle and distal bicep tendon stiffness evaluated using ultrasound elastography. BMC Medical Imaging 64:1. [Crossref]


17. Aleksandra Kisielewicz, Marcin Urbaniak, Adam Kawczyński. 2018. Effect of muscle energy technique on calf muscle stiffness increased after eccentric exercise in athletes. Journal of Kinesiology and Exercise Sciences 28:81, 21-29. [Crossref]

18. Lærke Tørring Kolding, Thien Phu Do, Caroline Ewertsen, Henrik Winther Schytz. 2018. Muscle stiffness in tension-type headache patients with pericranial tenderness. Cephalalgia Reports 1, 251581631876029. [Crossref]


